Residential Community with PV and Batteries: Reserve Provision under Grid Constraints

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Abstract
Technological advances in residential-scale batteries are paving the way towards self-sufficient communities to make the most use of their photovoltaic systems to support local energy consumption needs. To effectively utilize capabilities of batteries, the community can participate in the provision of short term operating reserve (STOR) services. To do so, adequate energy reserves in batteries are maintained during prescribed time windows to be utilized by electricity system operators. However, this may reduce energy sufficiency of the community. Further, the actual delivery of reserve could create distribution network congestions. To adequately understand the capability of a community to provide reserve, this work proposed a residential community energy management system formulated as a Mixed-Integer Linear Programming (MILP) model. This model aims to maximize energy sufficiency by optimal scheduling of batteries whilst considering reserve constraints. The model also maintains the aggregate power of houses within export/import limits that are defined offline using an iterative approach to ensure that the reserve provision does not breach distribution network constraints. The model is demonstrated on a residential community. The maximum committed reserve power with minimal impact on energy sufficiency is determined. Results also show that the capability of a community to provide reserve could be overestimated unless distribution network constraints are adequately considered.

Keywords: batteries, community management systems, distribution networks, energy storage, photovoltaics, sufficiency.

1. Introduction

Worldwide energy policies are expected to face a transition with a significant reduction in subsidies, due to the rapid cost reduction of various technologies, such as solar photovoltaics (PV) systems and battery storage systems, [1]. The drop in PV cost will also make the levelized cost of energy produced from PV cheaper than retail prices in many countries [2]. These changes will encourage consumption from self-produced energy rather than exporting excess generation to the grid, and, hence, reducing electricity bills [3]. One of the key solutions is the uptake of batteries. Indeed, excess generation throughout the day could be charged and then utilized to supply demand, particularly during evening and night periods [4].

However, the adoption of a simple controller to support each individual customers' energy needs may not help improve sufficiency of the electricity system as a whole. For instance, customers with high energy demands during night periods consume power from the grid without considering the potential opportunity of using the available stored energy in other neighbor consumers' batteries [5]. To make the most of PV, commercial arrangement can be adopted that enables group of customers in a geographic community to share the economic benefits of the installed PV and batteries [6, 7].

Although batteries may improve energy sufficiency, additional revenue stream may be needed to effectively utilize their capabilities [8]. The evolution of reserve services market in European countries (e.g., UK) provides opportunity for the community to create new revenue by participating as a Virtual Storage Plant (VSP) [9]. To do so, advanced community energy management is needed to coordinate the operation of individual batteries and aggregate their charging and discharging capabilities so they can be considered as a single unit by the electricity system operator to provide reserve services [10].

However, the provision of reserve could have a conflicting interaction with energy sufficiency of a community since adequate headroom and footroom should be made available during prescribed time windows to be utilized by the electricity system operator when required. Further, the delivery of reserve may create congestions and/or voltage issues on the distribution networks to which the community is connected.

In the literature, many models have been proposed in the context of self-sufficient communities. Most of the studies adopted single storage facility to increase self-sufficiency and reduce energy cost for a single customer [11] or a group of customers in a community [12, 13]. Although the framework in [14] showed the benefits of controlling multiple residential-scale batteries to

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increase sufficiency, distribution network constraints were not considered and additional grid services were not explored. To improve the economic viability of batteries, the studies in [15, 16] explored the provision of multiple grid services with a single battery and interactions between them. Few studies in the literature provided good understanding of the potential flexibility that could be achieved by aggregating residential-scale batteries as a VSP whilst limiting the power exchange of each house as proxy of distribution network constraints [17, 18]. But, the adopted power limits are assumed and not properly defined based on the network to which the community is connected.

Based on the above, none of the studies in the literature provides a comprehensive model able to determine the maximum reserve that a residential community with PV and batteries can provide with minimal impact on energy sufficiency and whilst respecting network constraints. This is important for several decision-makers, including electricity system operators and regulatory bodies, to both adequately determine the capability of a community to provide reserve and incentivize community operators when the provision of reserve reduces energy sufficiency.

To address the challenges described above, this work presents a community energy management system formulated as a Mixed-Integer Linear Programming (MILP) model that aims to maximize energy sufficiency of a residential community by the optimal scheduling of batteries whilst considering constraints related to both reserve services and distribution networks. The aggregated charging and discharging capabilities of individual batteries are managed so that the community becomes capable of providing the committed reserve within the availability windows. The model also maintains the aggregate power of houses in the community within export and import limits that are defined offline using an iterative approach to ensure that the delivery of reserve does not result in distribution network issues. This in turn allows the management of network constraints without the need of extensive network monitoring elements. This also provides substantial improvements relative to previous studies that either neglected network constraints or assumed arbitrary power threshold independent of the distribution network. To assess the impacts of reserve provision on sufficiency and the interactions with distribution network constraints, the model is run for different committed reserve so that the capability of a community to provide reserve is determined.

The rest of this paper is structured as follows: Section 2 provides an overview of a residential community energy management system with PV and batteries. Section 3 presents the formulation to model a community energy management system. Section 4 demonstrates the application of the framework on a case study considering 102 residential customers with PV and batteries connected to a low voltage (LV) network. Section 5 provides a discussion on the effects of using representative profiles compared to the adoption of a full yearly profile. Finally, conclusions are drawn in section 6.

2. Community Energy Management System: Overview

This section describes the model used to formulate a residential community energy management system. The modelling assumes the presence of a community operator that employs an optimization-based approach to maximize energy sufficiency of the community across an operational planning horizon (e.g., one day, one week) by the optimal control of residential batteries. Hence, the objective function is formulated to reduce imported energy of the community. To capture the seasonal and daily variations of PV and demand, the model is run for a set of time-series PV and load profiles so that the annual sufficiency of the community can be adequately assessed. For this purpose, full dataset of yearly time-series load and PV profiles could be adopted. Alternatively, a set of representative daily PV and load profiles could be also used to reduce the computational burden required to assess the annual energy sufficiency. A graphical illustration of this community system is given in Fig. 1.

The model is also subject to the following set of constraints to ensure that the community is able to provide reserve services whilst catering for distribution network constraints.

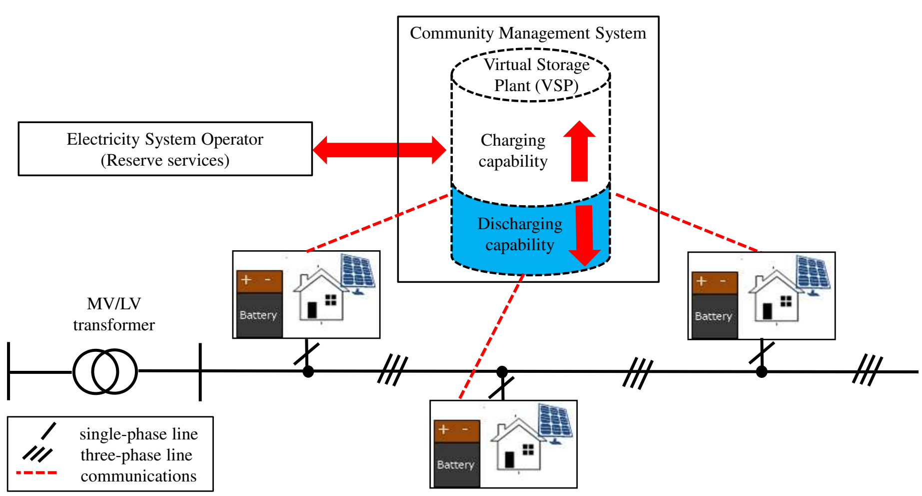

Fig. 1 Structure of residential community energy management system

2.1. Reserve Constraints

To allow the provision of reserve services, a set of constraints are needed to ensure the availability of sufficient headroom and footroom in batteries during prescribed time windows so the committed volume of reserve can be delivered when it is required by the electricity system operator. In particular, the provision of up reserve service requires that the sum of discharging capabilities of individual batteries is sufficient to deliver the committed up reserve power of the community. Further, the sum of charging capability of batteries defines the committed down reserve power of the community. The model also takes into account that reserve can be utilized in real time for the maximum duration of a reserve call (e.g., 30-min duration).

2.2. Distribution Network Constraints

Exercising the available rooms in batteries to deliver the required reserve may result in technical challenges particularly on residential LV distribution networks (to which residential PV and batteries are connected) such as voltage violations and congestions. Therefore, it is important to incorporate network constraints in the formulation of the community energy management system so that the capability of a community to provide reserve services can be adequately assessed.

However, the community energy management system may only deal in practice with measurements at houses (i.e. at customer side behind utility meters of houses) without having access to the distribution network and real-time measurements of network voltages and power flows. Further, the explicit modeling of network constraints in the optimization-based community energy management system will increase the complexity of the optimization engine. In particular, an AC Optimal Power Flow (OPF) formulated as a Mixed Integer Non-Linear Programming (MINLP) will be needed to drive the optimization-based community energy management system and define the decision variables (including the binary variables). Therefore, the computational burden will be increased significantly and the scalability of the problem will be limited.

To incorporate network constraints, the community energy management system maintains the aggregate power of individual houses within import and export limits defined 'off-line' so that thermal and voltage constraints are respected. In this regard, the power of batteries are managed to ensure that the delivery of reserve at any time period within the availability windows will not result in an aggregate power of houses outside the defined limits.

The limits are defined using the iterative approach presented in Fig. 2. The approach first produces a pool of the potential combinations of houses' net demand. To reduce computational burden (i.e., limiting the number of combinations), finite levels of net demand (import/export) are assumed for each house (e.g., 15 levels between -3.6 kW and 3.6 kW). The impact of a combination on voltages and LV line loadings is then assessed using a three-phase power flow model. Once a combination results in network issues, its aggregate power of houses' net demand (P^{agg}) will be considered as an infeasible limit. This aggregate power will be also removed from the feasible set of limits if it exists from other combinations considering that multiple combinations of houses' net demand may have the same aggregate power.

After all the combinations are explored and based on the sign of the aggregate powers (i.e., positive value is considered as import) registered in the set of feasible limits, sets of feasible import and export limits can be produced. The absolute maximum values of the produced import and export feasible sets are adopted as the defined limits.

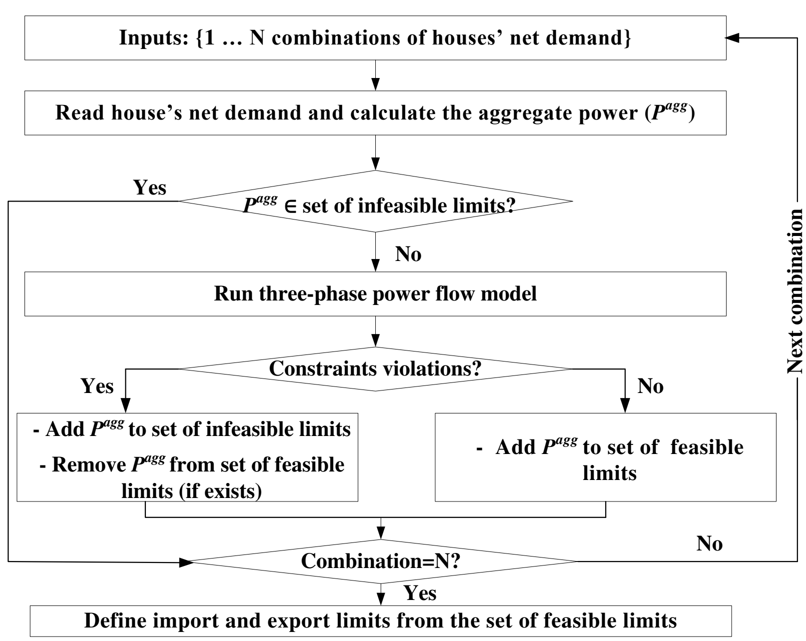

Fig. 2 Flowchart of the approach to define the export and import limits

3. Problem Formulation

This section presents the formulations of a community with group of residential houses (set H indexed by h, $H=\{1, 2, \ldots h\}$). Since the customers are residential with single-phase connection to the distribution network, the phase connection of each house is explicitly modelled. This provides a realistic modelling compared to previous studies in the literature that assumes the same connection phase to all the customers.

The power of a community $p_{\Phi,t}$ at each time step (set T indexed by t) and each phase (set Φ indexed by ϕ) is determined by aggregating the net demand of the individual houses ($p_{h,t}^{net}$) as given in (1).

$$p_{\phi,t} = \sum_{h\in H, \beta_h=\phi} p_{h,t}^{net} \quad \forall\, \phi, t \tag{1}$$

where $p_{\phi,t}$ could be either positive (import) or negative (export) and β_h is the phase connection of a house.

The power of a community $p_{\Phi,t}$ is also modelled by using two non-negative variables $\left(p_{\phi,t}^{\text{import}}, p_{\phi,t}^{\text{export}}\right)$ to represent import and export power, respectively, as given in (2).

$$p_{\phi,t} = p_{\phi,t}^{\text{import}} - p_{\phi,t}^{\text{export}}\ ;\ \forall\, \phi, t \tag{2}$$

To ensure that importing and exporting will not occur simultaneously, a binary variable is used to determine the status of the community for each phase, $x_{\phi,t}$, (e.g., $x_{\phi,t}=1$ means that the community at phase ϕ imports power from the grid). This in turn makes the formulation of the community energy management system as an MILP.

$$0 \le p_{\phi,t}^{\text{import}} \le\ x_{\phi,t}\, M\ ;\ \forall\, \phi, t \tag{3}$$

$$0 \le p_{\phi,t}^{\text{export}} \le\ \left(1 - x_{\phi,t}\right) M\ ;\ \forall\, \phi, t \tag{4}$$

where M is a large number selected to satisfy power needs of the community and allow charging/discharging batteries at their rated power.

As proxy of maximizing energy sufficiency of the community, the objective function is formulated in (5) to minimize imported energy of the community across a planning horizon of a day. In this respect, the optimization will reschedule the operation of batteries to increase the share of energy consumption that is supplied from PV so that the imported energy of the community is minimized.

$$min \sum_{t\in T} \sum_{\forall \phi \in \Phi} \left(p_{\phi,t}^{\text{import}}\right) \tag{5}$$

This objective is subject to a range of constraints including those related to the batteries, power balance at the house as well as reserve and distribution network constraints.

3.1. Storage Facilities

Batteries (set ST indexed by st) are controlled to discharge ($p_{st,t}^{dis}$) or charge ($p_{st,t}^{ch}$) active power, at each time step within the power rating, P_{st}^{rated}. The difference between the discharge and the charge power defines the output power of the battery (positive values of $p_{st,t}$ correspond to injection of power, i.e., discharging).

$$0 \le\ p_{st,t}^{dis} \le\ P_{st}^{rated}\ ;\ \forall\, st, t \tag{6}$$

$$0 \le\ p_{st,t}^{ch} \le\ P_{st}^{rated}\ ;\ \forall\, st, t \tag{7}$$

$$p_{st,t}\ = p_{st,t}^{dis} -\ p_{st,t}^{ch}\ ;\ \forall\, st, t \tag{8}$$

To ensure that charging and discharging actions of a battery are not applied simultaneously, the status of each battery is defined as a binary variable $z_{st,t}$, as given in (9)-(10).

$$0 \le p_{st,t}^{dis} \le\ \ z_{st,t} \times P_{st}^{rated}\ ;\ \forall\, st, t \tag{9}$$

$$0 \le p_{st,t}^{ch} \le\ \left(1 -\ z_{st,t}\right) \times P_{st}^{rated}\ ;\ \forall\, st, t \tag{10}$$

The model is also subject to a set of constraints that cater for energy ratings as well as the inter-temporal constraints of batteries [19]. The energy losses that result from energy and power conversion have to be accounted for during charging and discharging. Therefore, the change in the stored energy, $\Delta E_{st,t}^{stor}$, at each time step and the corresponding stored energy, $E_{st,t}^{stor}$, can be represented by (11) and (12), respectively.

$$\Delta E_{st,t}^{stor} = \left(\frac{p_{st,t}^{dis}}{\eta_{st}^{dis}} -\ p_{st,t}^{ch} \times \eta_{st}^{ch}\right) \times \Delta t \quad \forall\, st, t \tag{11}$$

$$E_{st,t}^{stor}\ =\ E_{st}^{(0)} - \textstyle\sum_{t=1}^{t} \Delta E_{st,t}^{stor} \quad \forall\, st, t \tag{12}$$

where η_{st}^{ch} and η_{st}^{dis} are the charging and discharging efficiencies, respectively. $E_{st}^{(0)}$ is the initial stored energy at the beginning of the planning horizon and Δt is the time step.

To preserve the lifetime of battery, the stored energy can be kept above a particular minimum stored energy level E_{st}^{min}. Therefore, the stored energy is controlled between a minimum level and its rated capacity (E_{st}^{rated}).

$$E_{st}^{min} \le E_{st,t}^{stor} \le E_{st}^{rated} \; ; \; \forall \, st, t \tag{13}$$

To cater for energy-dependency between consecutive days, the constraint in (14) is modelled so that the stored energy at the end of the day $E_{st}^{(N)}$ is equal to the initial stored energy $E_{st}^{(0)}$.

$$E_{st}^{(0)} = E_{st}^{(N)} \; ; \; \forall \, st \tag{14}$$

It is worth to highlight that above constraint can be relaxed by adopting a long operational planning horizon (i.e., multiple days), but this is at the expense of the computational burden.

3.2. Power Balances Equations

The net demand of a house is found using the power balance constraint in (15)

$$p_{h,t}^{net} = \sum_{d \in D | \beta_{d=h}} p_{d,t} - \sum_{g \in G | \beta_{g=h}} p_{g,t} - \sum_{st \in ST | \beta_{st=h}} p_{st,t}; \; \forall \, h, t \tag{15}$$

where $(p_{d,t})$ are the active power demand of houses (set D indexed by d); $p_{g,t}$ are the active power of PV systems (set G indexed by g) and β_u maps the location of demands, PV and batteries ($u \subset \{d, g, st\}$) to its associated house.

3.3. Reserve Constraints

To ensure that the community is able to provide the committed volume of reserve, additional constraints related to the output power and stored energy of batteries are modelled.

The maximum volume of up reserve $R_{st,t}^{up}$ and down reserve $R_{st,t}^{down}$ provided by each battery is limited by both its rating and output power as provided in (16) – (17). As shown in (16), the up reserve power provided by a battery is affected by the scheduled discharging power, whilst the down reserve is affected by the scheduled charging power, as given in (17).

$$p_{st,t} + R_{st,t}^{up} \le P_{st}^{rated} \; ; \; \forall \, st, t \tag{16}$$

$$p_{st,t} - R_{st,t}^{down} \ge -1 \times P_{st}^{rated} \; ; \; \forall \, \mathrm{st}, \mathrm{t} \tag{17}$$

The reserve provided by a battery for reserve call duration τ also depends on its stored energy and energy capacity. As shown in (18), sufficient footroom in battery has to be available to deliver a reserve of $R_{st,t}^{up}$ for τ duration, whilst the down reserve power is limited by the available headroom in the battery, as given in (19).

$$E_{st,t}^{stor} - \left(\frac{R_{st,t}^{up}}{\eta_{st}^{dis}} \right) \times \tau \ge E_{st}^{min}; \forall \, st, t \tag{18}$$

$$E_{st,t}^{stor} + R_{st,t}^{down} \times \eta_{st}^{ch} \times \tau \le E_{st}^{rated}; \; \forall \, st, t \tag{19}$$

The aggregate reserve capabilities of batteries within the availability windows is able to deliver the committed up and down reserve of the community $\left(R_t^{grid,up}, R_t^{grid,down}\right)$.

$$\sum_{st \in ST | \Phi_{st=\phi}} R_{st,t}^{up} \ge \left(R_t^{grid,up} / 3 \right); \forall \, \phi, t \tag{20}$$

$$\sum_{st \in ST | \Phi_{st=\phi}} R_{st,t}^{down} \ge \left(R_t^{grid,down} / 3 \right); \forall \, \phi, t \tag{21}$$

where $R_{st,t}^{up}$ and $R_{st,t}^{down}$ are zero outside the availability windows. It is also considered that the reserve required by the system operator is equally provided from each phase to prevent highly unbalanced loadings of distribution networks.

It is worth to highlight that the model is general and it can cater for seasonal-based availability windows and different length of a reserve call. Further, the aggregated reserve of individual batteries will not exceed the committed reserve of the community since the compliant to these constraints is achieved at the expense of energy sufficiency (i.e., affecting the objective function).

3.4. Distribution Network Constraints

To ensure that the delivery of reserve during the availability windows will not result in network issues, the aggregate power of individual houses taking into account the additional power due to the delivery of reserve should be maintained within the export and import limits $\left(p_{limit}^{export}, p_{limit}^{import}\right)$ defined using the approach in Section 2.2. To incorporate these limits in the modelling, the constraints in (22) and (23) are formulated.

$$- p_{\phi,t} + \sum_{st\in ST|\Phi_{st=\phi}} R_{st,t}^{up} \le p_{limit}^{export};\ \forall\, \phi, t \tag{22}$$

$$p_{\phi,t} + \sum_{st\in ST|\Phi_{st=\phi}} R_{st,t}^{down} \le p_{limit}^{import};\ \forall \phi, t \tag{23}$$

To determine the maximum up reserve that the community can provide whilst respecting distribution network constraints, the modelling is modified to consider that the PV output power production $p_{g,t}$, is controllable considering that PV power output can be curtailed This is important to ensure that the constraints in (22) are satisfied for any selected reserve power since the export limit defines the room for injections from both excess generation and the delivery of up reserve (discharge). The reserve power is increased progressively in steps and the volume of energy curtailment is assessed. The maximum reserve without curtailment is the maximum capability of the community to provide up reserve services (i.e., without the need to curtail PV power production).

The power output, $p_{g,t}$ at each time step are limited by the PV available power resource (defined as the product of the PV power rating, p_g^{rated}, and the normalized PV power pattern, Γ_t). This is presented in (24).

$$0 \le p_{g,t} \le \Gamma_t\, p_g^{rated};\ \forall\, g, t \tag{24}$$

To ensure that the application of curtailment is only adopted to solve network issues, the objective function in (5) is reformulated to also maximize the exported energy as given in (25).

$$min \sum_{t\in T} \sum_{\forall\phi\in\Phi} \left(\pi^{import} \times p_{\phi,t}^{\text{import}} - \pi^{export} \times p_{\phi,t}^{\text{export}}\right) \tag{25}$$

To ensure that the optimization engine provides the minimum imported energy (maximize energy sufficiency), the weighting coefficient related to the exported energy π^{export} is selected much smaller than the one used for the imported energy π^{import}.

4. Case Study: Applications

To model a residential community energy system, an LV feeder with 102 residential customers is adopted [20]. The LV feeder is fed from 11/0.433 kV transformer with tap ratio of 1.025:1. The corresponding single line diagram is shown in Fig. 3. The residential load profile for each individual customer is produced using the tool developed by the Centre for Renewable Energy Systems Technology (CREST [21].

The annual variations of PV power production profiles are modelled by using a set of daily PV profiles and their probabilities adopted from [22]. Half-hourly resolution is adopted. It is also considered that each customer has a 2 kW PV (a capacity that is not creating network issues) and a 2 kW/7 kWh battery with 1 kWh minimum stored energy. The round trip efficiency is set to 90%. [23]. It is worth to highlight that the formulation is generic to consider full dataset of yearly time-series load and PV profiles and with a long operational planning horizon (e.g., one week).

The benefits to coordinate batteries are explored using two case studies. First, batteries are managed to improve sufficiency. Second, batteries are controlled to provide up and down reserve services as a virtual storage plant. The same availability windows is adopted for the up and down reserve (07:00-13:00, 16:00-20:30) [18]. It is also considered that the duration of a reserve call is 30 minutes (τ=0.5 hour). The impact of reserve provision on sufficiency is assessed for different reserve power. Further, the interaction of reserve provisions with distribution network constraints is explored so that the maximum committed reserve level is determined.

The modeling language AIMMS [24] is used to formulate the community energy system and solved using the CPLEX solver. The distribution network analysis software package OpenDSS [25] is used to assess the impacts of reserve on the LV network and the definition of export and import limits.

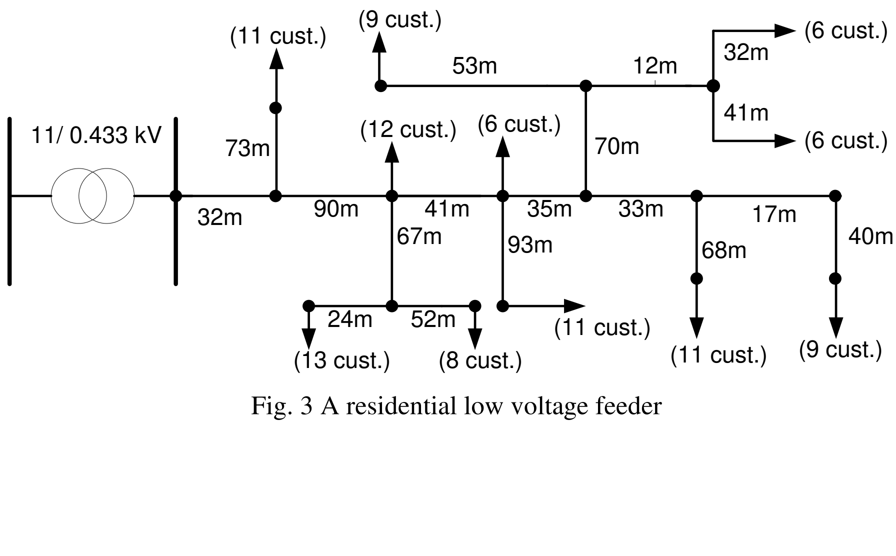

Fig. 3 A residential low voltage feeder

4.1. Self-Sufficient Community

Here, batteries are coordinated to maximize the local use of energy produced by PV (*coordinated control approach*). The analysis is demonstrated for a high PV production day in summer. The resultant net demand profile of the community is presented in Fig. 4 (red line) together with the profile without batteries (blue line). Since batteries harvest excess PV generation, it can be seen that the exported energy is significantly reduced particularly in mid of the day. The stored energy in batteries is then used to supply demand at night periods (i.e., reducing imported energy) so that electricity bill can be reduced. In particular, the imported energy falls to zero between 16:00 – 24:00. The reduction in both the exported and imported energy demonstrates the importance of batteries to achieve a more grid-independent community. For this day, the imported energy is reduced significantly from 568 kWh to 92 kWh (about 84%).

To understand the benefits of coordination, the results are compared against a *customer-led control approach* where each individual battery is controlled for the benefit of the customer (i.e., not for the benefit of the community). The net demand profile of the community is given in Fig. 5 (red line) together with the profile without batteries (blue line). Compared to the coordinated control approach (red line in Fig. 4), the customer-led control approach results in larger imported energy (e.g., see between 16:00 – 24:00) since the stored energy in other neighbor batteries are not used to supply the individual demand (77% larger imported energy than the coordinated control approach for this analyzed day).

To cater for the seasonal effects of PV and demand profiles, the yearly imported and exported energy as well as energy sufficiency of the community are all assessed by using the adopted set of representative PV and demand profiles. The results are presented in Table 1. It can be seen that the batteries can significantly increasing sufficiency. Even without coordination, 48% of the annual energy consumption of the community could be supplied from self-produced energy. The results also show the importance to coordinate batteries so that the annual energy sufficiency is increased to 54%.

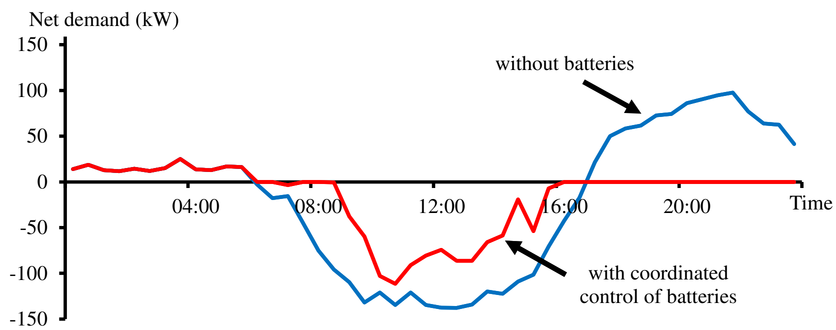

Fig. 4 Coordinated control: Net demand for a high PV production day

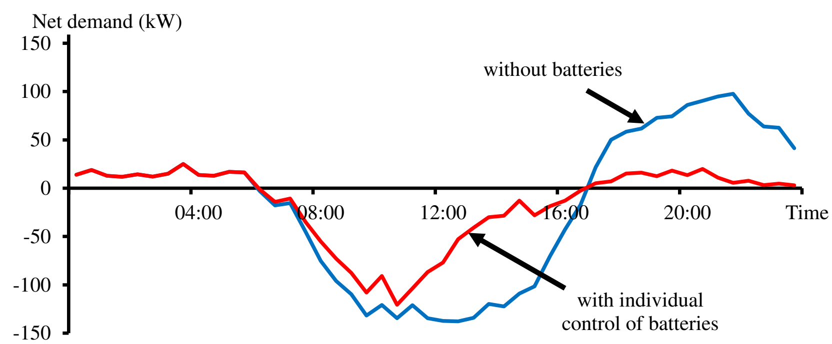

Fig. 5 Customer-led control (no coordination): Net demand for a high PV production day

Table 1
Annual performance metrics for customer-led and coordinated control approaches

Control approach	Imported energy (*MWh*)	Exported energy (*MWh*)	Energy Sufficiency (%)
Base case (demand-only)	395	0	0%
customer-led control approach (no coordination)	204	40	48%
With coordination	180	17	54%

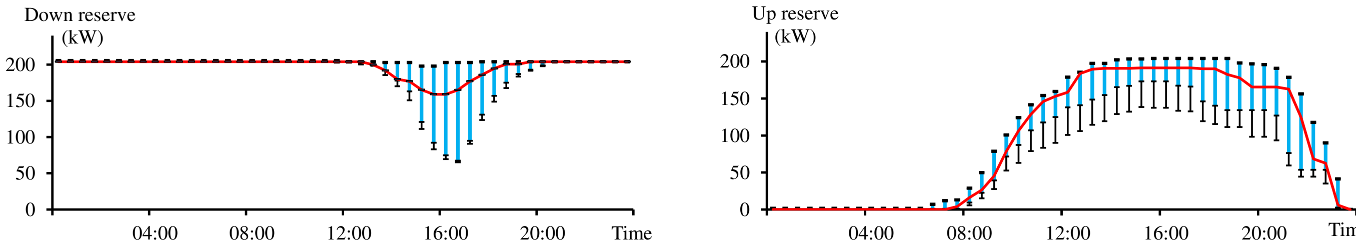

Fig. 6 Summer season: charging (down reserve) and discharging (up reserve) capability profiles of the community. The bottom of the box is the 25th percentile of the simulations. The top of the box is the 75th percentile of the simulations. The red line is the median of the simulations.

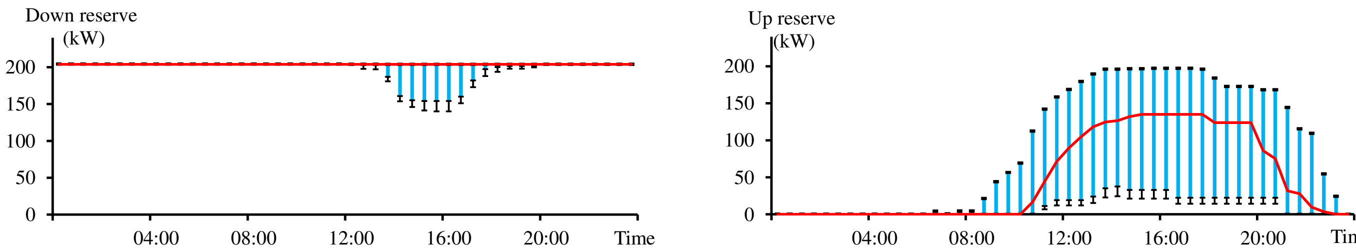

Fig. 7 Winter season: charging (down reserve) and discharging (up reserve) capability profiles of the community. The bottom of the box is the 25th percentile of the simulations. The top of the box is the 75th percentile of the simulations. The red line is the median of the simulations.

4.2. Flexibility for Reserve Services Provision

The adoption of batteries to only increase energy sufficiency will not effectively exploit their potential capabilities. For instance, batteries may not reach their energy capacities during low PV production days. Also, the volume of excess energy in a high-PV production day could be larger than the energy needs of the community. This in turn means that batteries could have headroom and footroom available to provide services to the system operator.

To assess the ability to provide grid services, the charging and discharging capabilities of individual batteries are determined at each time step considering both the energy store levels and ratings of batteries. The capability profiles of batteries are then aggregated and presented using boxplots for summer and winter seasons in Fig. 6 and Fig. 7.

In terms of charging capability (down reserve services), it can be seen that its maximum occurs at the early hours of the day in summer and winter (see Fig. 6 (left) and Fig. 7 (left) respectively). The corresponding median in both seasons can reach 204 kW (2kW/ battery). Since batteries charge excess generation during noon periods, the charging capability will become smaller. For example, the median in summer reaches its minimum close to 159 kW. However, the reduction in the charging capability in winter during noon periods is slightly reduced compared to the early hours of the day.

Further, the discharging capabilities (up reserve services) become larger when the stored energy in batteries increases. In this respect, the maximum discharging capabilities occurs between 12:00-18:00. This period corresponds to the time when most of batteries become fully charged from excess generation and before the start of discharging actions to supply demand. This can be seen in Fig. 6 (right) and Fig. 7 (right) for summer and winter seasons, respectively. Moreover, the discharging capability in summer is much higher than in winter season (i.e., larger PV production in summer).

4.3. Interaction between Reserve Provision and Sufficiency

Although the previous section shows that batteries could have headroom for charging and footroom for discharging, the volume of these rooms may not be sufficient to provide the required reserve. Further, the availability of these rooms may not occur at the same time periods (availability window) as required by the electricity system operator.

To illustrate the interaction between reserve provision and sufficiency, up and down reserve power of 204 kW is adopted (total ratings of batteries). The availability windows are between 07:00-13:00 and 16:00-20:30. The aggregate stored energy profile of individual batteries is presented in Fig. 8 (red line) together with the profile when batteries are only controlled to increase sufficiency (black line).

To make the community available to discharge 204 kW between 07:00-13:00 for 30 minutes, the aggregate stored energy in batteries has to be higher than 215 kWh at the start of this availability window considering the minimum allowable stored energy (102 kWh) and discharging efficiency. Since excess PV generation in the prior time periods (between 00:00 and 07:00) is not enough to achieve the required store level, batteries will be charged from the grid (i.e., higher stored energy with reserve at the early hours).

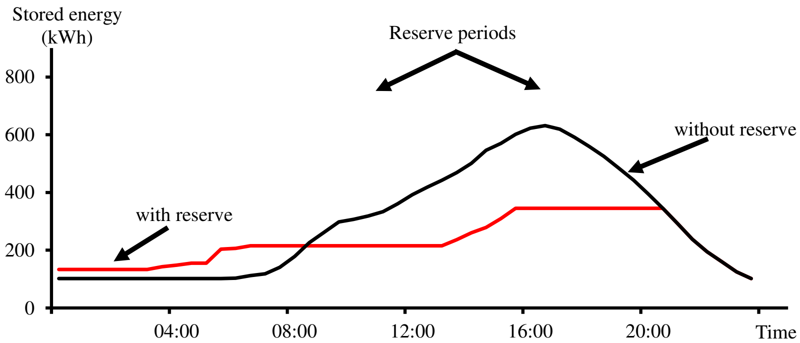

Fig. 8 Aggregate stored energy profile due to the provision of 204 kW up and down reserve during a high PV production day.

Table 2
Annual performance metrics for different reserve power

Average reserve per battery (kW)	Community committed reserve (kW)	Annual energy metrics: Imported energy (*MWh*)	Exported energy (*MWh*)	Sufficiency (%)
0.25	25.5	182	18	54.0%
0.5	51	183	19	53.6%
0.75	76.5	185	21	53.2%
1	102	186	22	52.8%
1.25	127.5	189	25	52.1%
1.5	153	198	33	50.0%
1.75	178.5	214	51	45.9%
2	204	239	74	39.4%

Further, the provision of 204 kW down reserve (charging) between 16:00-20:30 for 30 minutes requires the availability of adequate headroom in batteries. To do so, excess generation is exported to the grid in the prior time periods instead of storing it (i.e., smaller stored energy with reserve between 07:00-13:00). Moreover, the provision of up reserve (discharging) between 16:00-20:30 requires maintaining the stored energy instead of using it to supply the demand. The results for this day clearly demonstrate that the provision of reserve reduces sufficiency.

To adequately assess the impact of reserve provision, the yearly imported and exported energy as well as energy sufficiency are all found considering eight reserve power from 25.5 kW (in average 0.25 kW/battery) up to 204 kW (total ratings of batteries) in steps of 25.5 kW. The results are presented in Table 2.

It can be seen that the community could provide a reserve power up to 127.5 kW (about 64% of the total ratings of batteries) without significantly reducing sufficiency (less than 2% reduction). However, the provision of larger reserve will increase both the imported and exported energy and thus reducing sufficiency. For example, the use of 204 kW reserve reduces sufficiency from 54% to 39.4%. To encourage the participation in reserve provision, the electricity system operator should provide adequate compensation for reduction in sufficiency.

Further, the selection of reserve power could be different between summer and winter. To understand the seasonal implications of reserve provision and energy sufficiency, the above analysis is carried out for summer and winter seasons and considering different reserve power. The results are provided in Table 3. It is found that the relative reduction in energy sufficiency due to the provision of reserve is much higher in summer. For instance, the reduction in energy sufficiency in summer could reach 26% for the provision of a reserve power of 204 kW (in average 2 kW/battery) compared to only 5% in winter. This in particular due to the need to define adequate head rooms in the batteries to be available to provide down reserve services (charging) between 16:00-20:30. Therefore, the volume of charged energy in the batteries during noon periods will be restricted particularly for high PV energy production days in summer. This in turn will limit the usage of PV excess energy to supply the demand during night periods. The results also show that larger reserve power could be provided during winter season without significantly reducing energy sufficiency (in average 1.75 kW/battery) compared to summer (in average 1.25 kW/battery).

4.4. Interaction between Reserve Provision and Distribution Network Constraints

Here, voltages and loadings of LV lines are assessed for a high PV production day due to the delivery of 204 kW of up and down reserve power. This reserve power corresponds to maximum reserve that could be provided within the ratings of batteries (i.e., 2 kW/battery). Since the time to deliver reserve is determined by the system operator, the impacts are found for all the time periods within the availability windows. This is done assuming 30-minute reserve delivery duration.

Table 3
Energy sufficiency in summer and winter for different reserve power

Average reserve per battery (kW)	Community committed reserve (kW)	Energy Sufficiency (%)	
		Summer	Winter
Base case (demand-only)	0	75%	36%
0.25	25.5	75%	36%
0.5	51	74%	35%
0.75	76.5	73%	35%
1	102	72%	35%
1.25	127.5	71%	35%
1.5	153	67%	35%
1.75	178.5	60%	34%
2	204	49%	31%

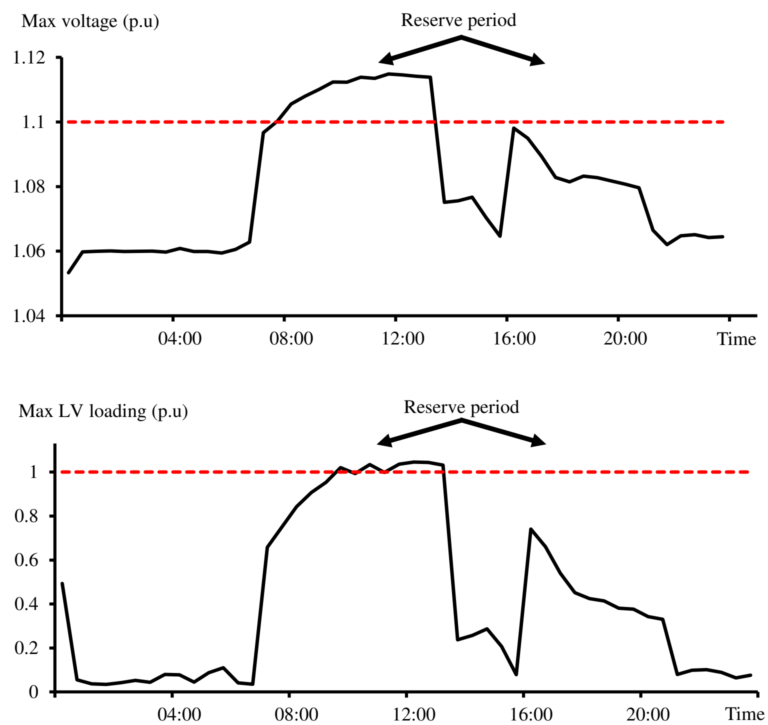

Fig. 9 (top) Voltages and (bottom) loading of LV lines due to the delivery of 204 kW up reserve on a high PV production day

The results show that although the community can create available rooms to provide reserve, exercising these rooms result in network issues. Fig. 9, (top) shows that the delivery of up reserve power increases customers' voltages above the upper statutory limit (1.1 p.u.) particularly if the reserve is required at the same time periods with high PV generation (excess generation from each house is increased with the delivery of reserve). Also, the loading of LV lines are exceeding their thermal limits, albeit small excursions (as shown in Fig. 9, bottom). Though, it is found that the provision of down reserve services (i.e., charging) is harmless as it does not present voltage and congestion issues for all the time steps within the availability windows.

4.5. Management of Distribution Network Constraints

To cater for network constraints, the aggregate power of individual houses taking into account the additional power due to the delivery of reserve should be maintained within the export and import limits that are defined using the process in Section 2.2. In this respect, a pool of the potential combinations of houses' net demand is produced considering that each house can have net demand between -3.6 kW and 3.6 kW. Voltages and loadings of LV lines are found for all the combinations of houses' net demand up to 367.2 kW (3.6 kW per house).

It can be seen in Fig. 10 that voltages are within the limits for all the combinations with aggregate export power smaller than 160.5 kW. As the export power becomes significant, the percentage of combinations with network issues increases. For instance, the upper statutory voltage limit is violated for less than 1% of the combinations with an aggregate export of 200 kW compared

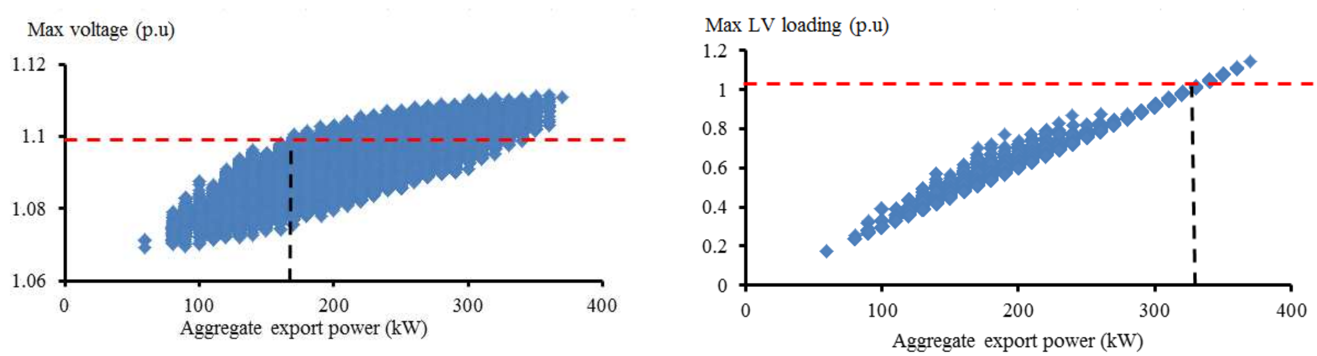

Fig. 10 (left) maximum voltage and (right) maximum loading of LV lines versus different aggregate export power

Table 4
Energy curtailment for different up reserve power

Average reserve per battery (kW)	Community committed reserve (kW)	Energy curtailment (%)
0.25	25.5	0%
0.5	51	0%
0.75	76.5	0%
1	102	0%
1.25	127.5	0.7%
1.5	153	6.9%
1.57	160.5	10.8%

Table 5
Energy curtailment for different up reserve power in winter and summer seasons

Average reserve per battery (kW)	Community committed reserve (kW)	Energy curtailment (%)	
		Summer	Winter
0.25	25.5	0%	0%
0.5	51	0%	0%
0.75	76.5	0%	0%
1	102	0%	0%
1.25	127.5	1%	0%
1.5	153	10%	0.6%
1.57	160.5	15%	1.4%

to 60% when the export reaches 300 kW. Further, the loadings of LV lines exceed their thermal limits with an aggregate export power larger than 330 kW. This shows that voltage rise issues are more critical for this network. To ensure that the scheduling of batteries will not breach network constraints, a conservative export limit of 160.5 kW is adopted. This limit corresponds to the maximum aggregate export whose all combinations are not resulting in network issues.

Similarly, the import limit is determined by assessing the effects of all the potential combinations of houses net demands on voltage drop and loadings of LV lines. It is found that thermal issues can occur with an aggregate import power larger than 330 kW, whilst voltages are kept within limits for all the potential aggregate net demand (0 kW – 367.2 kW). In this respect, the import limit is defined as 330 kW. The adoption of larger import limit than the export limit shows that the community is able to deliver larger volumes of down reserve power compared to its ability to deliver up reserve.

To determine the maximum up reserve that could be provided by the community, it is considered that the PV output power production is controllable and can be subject to curtailment. This is done since the export limit defines the room for injections from both excess generation and the delivery of up reserve.

The energy curtailment required to respect network constraints is found for different up reserve power up to 160.5 kW (the defined export limit). As shown in Table 4, the maximum up reserve without the need to PV curtailment is 102 kW (in average 1 kW/battery), which corresponds to only 50% of the total ratings of batteries. This highlights the importance to consider network constraints to adequately define the maximum up reserve provided by the community without overestimation. However, the maximum up reserve could be different between summer and winter. To understand the difference in the maximum up reserve that could be provided in winter and summer seasons within distribution network constraints, the above analysis is repeated per season and the results are given in Table 5. It can be seen that curtailment is only required in winter for a reserve larger than

127.5 kW (in average 1.25 kW/battery) compared to 102 kW (in average 1 kW/battery) in summer. Also, the maximum volume of curtailment in winter reaches 1.4% compared to 15% in summer. This indeed highlights that the community is able to deliver larger up reserve power in winter season with minimal impacts on the distribution network compared to summer.

It is also worth to highlight the provision of larger reserve in summer is possible by controlling PV power production. However, this will result in larger volume of curtailment and will reduce the energy sufficiency.

5. Effects of Using Representative Daily PV Profiles on the Community Energy management System

The case studies in Section 4 are carried out based on a set of daily PV profiles directly adopted from [22] and considering one-day operational planning horizon. To understand the extent that the performance of the community energy management system with a set of representative daily PV profiles is equivalent to the adoption of full dataset of yearly time-series PV production profiles, the following process is done. A real UK half-hourly PV profile for one year is input to the community energy management system considering one-week operational planning horizon. The community energy management system is employed to maximize the local use of energy produced by PV. The results are compared against the adoption of a set of representative daily PV profiles produced using the approach presented in [22] and based on the adopted annual PV data.

The simulation results show that the energy sufficiency of the community by using the full dataset of yearly time-series PV production profiles are very close to the one obtained with the set of representative profiles. In particular, the difference in energy sufficiency is smaller than 0.6%. Also, the adoption of representative profiles allows reducing significantly the computational burden. Indeed, the simulation time is reduced to 14 seconds compared to 387 seconds with the yearly simulation case study. It is also worth to highlight that the expansion of the planning horizon to one week allows better catering for the energy-dependency between consecutive days and therefore reducing the need to additional constraints required in the one-day planning horizon. However, the need to adopt long planning horizon might be more needed when multiple grid services are provided by the community.

6. Conclusions

This work presents a residential community energy management system formulated as a Mixed-Integer Linear Programming (MILP) model that aims to maximize energy sufficiency of community with PV by optimal scheduling of batteries whilst considering constraints related to both reserve services and distribution networks. The model also maintains the aggregate power of houses in the community within defined export and import limits so that the delivery of reserve will not result in thermal and voltages issues. The limits are found by using an iterative approach that searches for the maximum aggregate power of houses' net demand (import/export) whilst respecting network constraints for all the possible combinations of individual houses' power. The adoption of limits reduces the need to extensive network monitoring elements and avoids the computational burden that would be otherwise needed by the explicit modelling of distribution network constraints in the optimization-based community energy management system.

The model is demonstrated using a residential community that consists of residential customers with PV and batteries connected to a low voltage distribution feeder. The results demonstrate the benefits to coordinate batteries in increasing energy sufficiency of the community compared to the adoption of a controller per house to only support each individual customers' energy needs. The coordination also allows the provision of up and down reserve power to the electricity system operator by harnessing the available headroom and footroom in batteries. However, the provision of large reserve power will be at the expense of energy sufficiency, particularly in summer season. This in turn requires adequate regulatory incentive schemes to compensate for the reduction in sufficiency.

It is also found that the incorporation of distribution network constraints allows better understanding of the community ability to provide reserve. The results show that the community is able to deliver larger down reserve than its ability to deliver up reserve. Also, the maximum up reserve that could be provided by the community will be overestimated unless network constraints are considered. Further, it is found that the impacts on the distribution network due to the provision of up reserve power are much smaller in winter compared to summer.

References

[1] "UK solar beyond subsidy: the transition," Renewable Energy Association (REA), UK, 2015.

[2] "Technology roadmap: Solar Photovoltaic energy," International Energy Agency (IEA), France, 2014.

[3] "Best practices on renewable energy self-consumption," European Commission, Brussels, 2015.

[4] "Development of decentralised energy and storage systems in the UK," Renewable Energy Association (REA), UK, 2016.

[5] A. Lever, D. Sanders, N. Lehmann, M. Ravishankar, M. Ashcroft, G. Strbac*, et al.* (2016). *Can storage help reduce the cost of a future UK electricity system*.

[6] "Community energy state of the sector," Community Energy England, UK, 2017.

[7] Y. Zhou, J. Wu, and C. Long, "Evaluation of peer-to-peer energy sharing mechanisms based on a multiagent simulation framework," *Applied energy,* vol. 222, pp. 993-1022, 2018.

[8] "Electricity storage guide for communities and independent developers," Energy Networks Association (ENA), UK, 2017.

[9] "Wider access to the balancing mechanism roadmap," National Grid, UK, 2018.

[10] X. He, E. Delarue, W. D'haeseleer, and J.-M. Glachant, "A novel business model for aggregating the values of electricity storage," *Energy Policy,* vol. 39, pp. 1575-1585, 2011.

[11] A. S. Hassan, L. Cipcigan, and N. Jenkins, "Optimal battery storage operation for PV systems with tariff incentives," *Applied Energy,* vol. 203, 2017.

[12] A. Fleischhacker, H. Auer, G. Lettner, and A. Botterud, "Sharing solar PV and energy storage in apartment buildings: resource allocation and pricing," *IEEE Transactions on Smart Grid,* vol. 10, 2019.

[13] C. P. Mediwaththe, E. R. Stephens, D. B. Smith, and A. Mahanti, "Competitive energy trading framework for demand-side management in neighborhood area networks," *IEEE Transactions on Smart Grid,* vol. 9, pp. 4313 - 4322, 2018.

[14] C. Long, J. Wu, Y. Zhou, and N. Jenkins, "Peer-to-peer energy sharing through a two-stage aggregated battery control in a community Microgrid," *Applied Energy,* vol. 226, pp. 261-276, 2018.

[15] E. Namor, F. Sossan, R. Cherkaoui, and M. Paolone, "Control of battery storage systems for the simultaneous provision of multiple services," *IEEE Transactions on Smart Grid* vol. 10, 2019.

[16] R. Moreira, R. Moreno, and G. Strbac, "Synergies and conflicts among energy storage services," presented at the IEEE International Energy Conference (Energycon), Leuven, Belgium, 2016.

[17] N. Good and P. Mancarella, "Modelling and assessment of business cases for smart multi-energy districts," presented at the Power Systems Computation Conference (PSCC), Genoa, Italy, 2016.

[18] N. Good and P. Mancarella, "Flexibility in multi-energy communities with electrical and thermal storage: A stochastic, robust approach for multi-service demand response," *IEEE Transactions on Smart Grid,* vol. 10, 2019.

[19] S. W. Alnaser and L. F. Ochoa, "Optimal sizing and control of energy storage in wind power-rich distribution networks," *IEEE Transactions on Power Systems,* vol. 31, 2016.

[20] I. H. Gil, "Integrated assessment of quality of supply in future electricity networks," 2014.

[21] I. Richardson and M. Thomson. (2010). *Domestic electricity demand model simulation example*. Available: http://hdl.handle.net/2134/5786

[22] S. W. Alnaser and L. F. Ochoa. (2017). *Final Report for WP 1.1 and 1.2 "Wide-Scale Adoption of PV in UK Distribution Networks"*. Available: http://www.energy.manchester.ac.uk/media/eps/manchester-energy/wisepv/UoM_WISE-PV_WP1.1-1.2_FinalReport_v1.pdf

[23] S. Schoenung, "Energy storage systems cost update," Sandia National Laboratories, Albuquerque, New Mexico, 2011.

[24] J. Bisschop and M. Roelofs, "AIMMS - The User's Guide," Paragon Decision Technology, 2006.

[25] R. Dugan and T. E. McDermott, "An open source platform for collaborating on smart grid research," presented at the IEEE/PES General Meeting 2011, 2011.